

PLASMA INDUCED NEUTRINO SPIN FLIP VIA THE NEUTRINO MAGNETIC MOMENT

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Abstract

The neutrino spin flip radiative conversion processes $\nu_L \rightarrow \nu_R + \gamma^*$ and $\nu_L + \gamma^* \rightarrow \nu_R$ in medium are considered. It is shown in part that an analysis of the so-called spin light of neutrino without a complete taking account of both the neutrino and the photon dispersion in medium is physically inconsistent.

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1 Introduction

The most important event in neutrino physics of the last decades was the solving of the Solar neutrino problem. The Sun appeared in this case as a natural laboratory for investigations of neutrino properties. There exists a number of natural laboratories, the supernova explosions, where gigantic neutrino fluxes define in fact the process energetics. It means that microscopic neutrino characteristics, such as the neutrino magnetic moment, etc., would have a critical impact on macroscopic properties of these astrophysical events.

One of the processes caused by the photon interaction with the neutrino magnetic moment, which could play an important role in astrophysics, is the radiative neutrino spin flip transition $\nu_L \rightarrow \nu_R \gamma$. The process can be kinematically allowed in medium due to its influence on the photon dispersion, $\omega = |\mathbf{k}|/n$ (here $n \neq 1$ is the refractive index), when the medium provides the condition $n > 1$. In this case the effective photon mass squared is negative, $m_\gamma^2 \equiv q^2 < 0$. This corresponds to the well-known effect of the neutrino Cherenkov radiation [1].

There exists also such a well-known subtle effect as the additional energy W acquired by a left-handed neutrino in plasma. This additional energy was considered in the series of papers by Studenikin et al. [2] as a new kinematical possibility to allow the radiative neutrino transition $\nu_L \rightarrow \nu_R \gamma$. The effect was called the “spin light of neutrino”. For some reason, the photon dispersion in medium providing in part the photon effective mass, was ignored in these papers. However, it is evident that a kinematical analysis based on the additional neutrino energy in plasma (caused by the weak forces) when the plasma influence on the photon dispersion (caused by electromagnetic forces) is ignored, cannot be considered as a physical approach. In this paper, we perform a consistent analysis of the radiative neutrino spin flip transition in medium, when its influence both on the photon and neutrino dispersion is taken into account.

2 Cherenkov process $\nu_L \rightarrow \nu_R \gamma$ and its crossing $\nu_L \gamma \rightarrow \nu_R$

Let us start from the Cherenkov process of the photon creation by neutrino, $\nu_L \rightarrow \nu_R \gamma$, which should be appended by the crossed process of the photon absorption $\nu_L \gamma \rightarrow \nu_R$. At this stage we neglect the additional left-handed neutrino energy W , which will be inserted below. For the $\nu_L \rightarrow \nu_R$ conversion width one obtains by the standard way:

$$\begin{aligned} \Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}} &= \Gamma_{\nu_L \rightarrow \nu_R \gamma} + \Gamma_{\nu_L \gamma \rightarrow \nu_R} = \frac{\mu_\nu^2}{16 \pi^2 E} \int j_\alpha j_\beta^* \sum_{\lambda=t,\ell} \varepsilon_{(\lambda)}^{*\alpha} \varepsilon_{(\lambda)}^\beta Z_\gamma^{(\lambda)} \frac{d^3 \mathbf{p}'}{E'} \\ &\times \left\{ \frac{\delta(E - E' - \omega)}{2\omega} [1 + f_\gamma(\omega)] + \frac{\delta(E - E' + \omega)}{2\omega} f_\gamma(\omega) \right\}, \end{aligned} \quad (1)$$

where $\varepsilon_{(\lambda)}^\alpha$ is the photon polarization vector, j^α is the Fourier transform of the neutrino magnetic moment current, $p^\alpha = (E, \mathbf{p})$, $p'^\alpha = (E', \mathbf{p}')$ and $q^\alpha = (\omega, \mathbf{k})$ are the four-momenta of the initial and final neutrinos and photon, respectively, $\lambda = t, \ell$ mean transversal and longitudinal photon polarizations, $f_\gamma(\omega) = (e^{\omega/T} - 1)^{-1}$ is the Bose–Einstein photon distribution function, and $Z_\gamma^{(\lambda)} = (1 - \partial \Pi_{(\lambda)} / \partial \omega^2)^{-1}$ is the photon wave-function renormalization. The functions $\Pi_{(\lambda)}$, defining the photon dispersion law:

$$\omega^2 - \mathbf{k}^2 - \Pi_{(\lambda)}(\omega, \mathbf{k}) = 0, \quad (2)$$

are the eigenvalues of the photon polarization tensor: $\Pi_{\alpha\beta} \varepsilon_{(\lambda)}^\beta = \Pi_{(\lambda)} \varepsilon_{(\lambda)\alpha}$.

The width $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$ can be rewritten to another form. Let us introduce the energy transferred from neutrino: $E - E' = q_0$, which is expressed via the photon energy $\omega(k)$ as $q_0 = \pm \omega(k)$. Then δ -functions in Eq. (1) can be rewritten:

$$\frac{\delta(q_0 \mp \omega(k))}{2\omega(k)} = \delta(q_0^2 - \omega^2(k)) \theta(\pm q_0). \quad (3)$$

Transforming the δ -function to have the dispersion law in the argument:

$$\delta(q_0^2 - \omega^2(k)) = \left[Z_\gamma^{(\lambda)} \right]^{-1} \delta(q^2 - \Pi_{(\lambda)}(q)), \quad (4)$$

one can see that the renormalization factor $Z_\gamma^{(\lambda)}$ is cancelled in the conversion width (1). Integration in Eq. (1) with the δ -function (4) can be easily performed when the function $\Pi_{(\lambda)}(q)$ is real. However, it has, in general, an imaginary part. It means, that the photon is unstable in plasma.

3 Generalization to the case of unstable photon

In the case, when the eigenfunction $\Pi_{(\lambda)}(q)$ has an imaginary part, one should use instead of the δ -function its natural generalization of the Breit–Wigner type, with e.g. the retarded functions $\Pi_{(\lambda)}(q)$:

$$\delta(q^2 - \Pi_{(\lambda)}(q)) \Rightarrow \frac{1}{\pi} \frac{-\text{Im } \Pi_{(\lambda)} \text{ sign}(q_0) \epsilon_\lambda}{(q^2 - \text{Re } \Pi_{(\lambda)})^2 + (\text{Im } \Pi_{(\lambda)})^2}, \quad (5)$$

where $\epsilon_\lambda = +1$ for $\lambda = t$ and $\epsilon_\lambda = -1$ for $\lambda = \ell$.

After some transformations, taking into account the additional energy W acquired by a left-handed neutrino in plasma, and changing the integration variables from the final neutrino 3-momentum to the photon energy and momentum, $d^3\mathbf{p}' \rightarrow dq_0 dk$ ($k \equiv |\mathbf{k}|$), one obtains:

$$\begin{aligned} \Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}} &= \frac{\mu_\nu^2}{16 \pi^2 E^2} \int_{-\infty}^{E+W} dq_0 \int_{|q_0-W|}^{2E+W-q_0} \frac{dk}{k} [1 + f_\gamma(q_0)] (2E - q_0)^2 q^4 \\ &\times \left\{ \left(1 - \frac{k^2}{(2E - q_0)^2} \right) \left[1 - \frac{2q_0 W}{q^2} + \frac{8E(E - q_0)W^2}{q^4 [(2E - q_0)^2/k^2 - 1]} \right] \varrho_{(t)}(q_0, k) \right. \\ &\left. - \left(1 - \frac{2q_0 W}{q^2} \right) \varrho_{(\ell)}(q_0, k) \right\}, \end{aligned} \quad (6)$$

where $q^2 = q_0^2 - k^2$, and the photon spectral density functions are introduced:

$$\varrho_{(\lambda)} = \frac{2(-\text{Im } \Pi_{(\lambda)})}{(q^2 - \text{Re } \Pi_{(\lambda)})^2 + (\text{Im } \Pi_{(\lambda)})^2}. \quad (7)$$

Our formula (6) having the most general form, can be used for neutrino-photon processes in any optically active medium. We only need to identify the photon spectral density functions $\varrho_{(\lambda)}$.

4 Does the window for the “spin light of neutrino” exist?

To show manifestly that the case considered in the papers by Studenikin et al. [2], with taking the additional left-handed neutrino energy W in plasma and ignoring the photon dispersion, was really unphysical, let us consider the region of integration for the width $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$ in Eq. (6). In Fig. 1, the photon vacuum dispersion line $q_0 = k$ is inside the allowed kinematical region (left plot), but the plasma influenced photon dispersion curve appears to be outside, if the neutrino energy is not large enough (right plot).

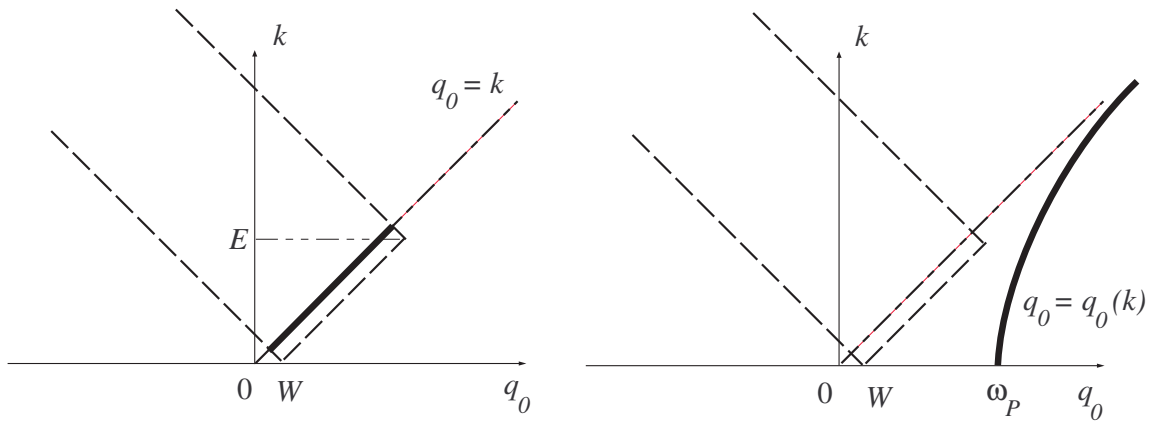


Figure 1: The region of integration for the width $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$ with the fixed initial neutrino energy E is inside the slanted rectangle shown by dashed line. The vacuum photon dispersion (if the medium influence is ignored) is shown by bold line in the left plot. The photon dispersion curve in plasma is shown by bold line in the right plot.

For the fixed plasma parameters, the threshold neutrino energy E_{\min} exists for coming of the dispersion curve into the allowed kinematical region. Even for the interior of a neutron star this threshold neutrino energy is rather large: $E_{\min} \simeq \omega_P^2/(2W) \simeq 10 \text{ TeV}$, where ω_P is the plasmon frequency.

One could hope that the “spin light of neutrino” may be possible at ultra-high neutrino energies. However, in this case the local limit of the weak interaction is incomplete, and the non-local weak contribution into additional neutrino energy W must be taken into account. This contribution always has a negative sign, and its absolute value grows with the neutrino energy. One could only hope that the window arises in the neutrino energies for the process to be kinematically opened, $E_{\min} < E < E_{\max}$. For example, in the solar interior there is no window for the process with electron neutrinos at all. A more detailed analysis of this subject was performed in our papers [3, 4].

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